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Analysis of environmental benefits associated with the incorporation of Waelz slag into fired bricks using LCA

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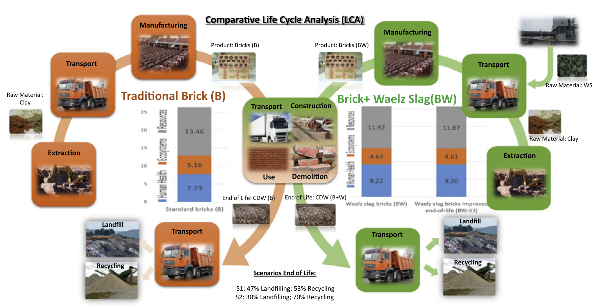
HIGHLIGHTS

- Impact on climate change of bricks incorporating Waelz slag is reduced by 11.8%.
- Waelz slag bricks benefit from impact savings affecting human toxicity category.
- Higher air emissions during firing offset benefits due to soil emission savings.
- Overall environmental benefits of Waelz slag incorporation to bricks is marginal.
- Increased CDW recycling does not improve environmental performance.

GRAPHICAL ABSTRACT



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ABSTRACT

A comparative cradle-to-grave LCA shows that incorporating Waelz slag into ceramic bricks generates lower impact on climate change and reduces the impact on freshwater ecotoxicity and fossil depletion. These benefits are attributable to impact savings due to avoiding the landfilling of the slag and reduced fuel demand during the manufacturing stage. However, due to the higher SO_2 and HF emissions generated in the firing of slag containing bricks, these benefits are offset by higher impacts on human toxicity and terrestrial acidification categories. The aggregated results suggest very limited environmental benefits in this practice even taking into account different end-of-life scenarios.

1. Introduction

The construction sector is increasingly concerned about the application of Industrial Ecology (IE) principles that improve the environmental performance of building materials. The incorporation of industrial residues into construction products is receiving attention as a means to achieve two objectives: first, minimizing the amount of potentially harmful residues destined for disposal; and second, reducing the consumption of natural resources and energy in the manufacturing of the final materials [1–4].

These principles are reflected in the Construction Products Regulation (CPR) 305/2011/EC [5], which lays down harmonised conditions for the marketing of construction products in the European Union (EU). Annex I of this Regulation contains a list of Basic Requirements for Construction Works (BRCW) that must be satisfied by any construction material before it may be granted permission to be used and commercialized in the EU. One of these requirement categories (BRCW 3 – Hygiene, health and the environment) provides conditions to be fulfilled regarding the emission

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of substances that may damage the environment and human health, including greenhouse gas emissions. In this respect, the regulation recognizes the need to minimize the emission of harmful substances to the atmosphere, waters and soil. Another category (BRCW 7 – Sustainable use of natural resources) is dedicated to the use of raw materials in an environmentally conscious manner. This category focuses on the use of materials that are recyclable and compatible with the surrounding environment in terms of degradability and harmlessness at the end of their useful lives. CPR sustains the need to use a life cycle approach to evaluate the environmental performance of construction materials, thus considering impacts attributable to all stages in its value chain from raw material extraction to final disposal. The technical implementation of this life cycle approach is described in *EN 15804 Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products* [6].

In line with these ideas, experimental results have been particularly promising regarding the incorporation of Waelz slag into fired bricks. This inorganic residue, consisting of a mixture of Fe_2O_3 (56%) and CaO (16%) [7], is generated in large amounts in Waelz plants dedicated to the industrial recovery of ZnO/PbO from Electric Arc Furnace dust [8]. This slag is classified in the European List of Waste [9] as a non-hazardous waste. However, its disposal by landfilling represents a serious environmental risk and involves considerable economic costs for this industrial activity. Experimental investigations have proven the optimum technological properties of ceramic bricks incorporating up to 20% Waelz slag and the reduced energy requirements involved in the firing process [8]. Despite potential benefits, the commercial production of bricks containing waste materials is still very marginal. This has been associated in part to unclear transmission of information to industry and the public in general regarding the environmental soundness of these materials [1] and also the limited amount of work dedicated to evaluate the overall environmental benefits of this approach. However, European strategies, like the Action Plan for Circular Economy [10], can contribute to enhance the benefits of reintroduce waste flows to new production processes. The proposed actions will contribute to "closing the loop" of product lifecycles through greater recycling and re-use, and bring benefits for both the environment and the economy.

Life Cycle Assessment (LCA) is a methodology widely used to quantify potential impacts and damage to the environment associated with process and products, including the value chain of construction materials [11,12]. LCA conducted on standard products from the brick manufacturing industry [13–16] have shown that environmental impacts are primarily associated with energy consumption in the firing process. Impact on climate change reported in the literature for fired clay bricks usually range between 132 and 295 kg of CO_2 eq./tonne of brick [15,17,18], depending primarily on the scope of the LCA, characteristics of the firing process and brick quality. The use of LCA to investigate the benefits of waste incorporation into fired bricks is very limited. Bories et al. [19] applied a cradle to gate approach to demonstrate the improved performance of fired clay bricks when incorporating agricultural wastes as pore forming agent.

The aim of this investigation is to provide additional information about the environmental consequences of incorporating Waelz slag into fired bricks. The analysis has been performed using LCA methodology and a cradle to grave approach. The analyses have been carried out using primary inventory data obtained experimentally for the emission of air pollutants during the firing process and for the leaching of potentially toxic inorganic species in landfill sites at the end of the useful lives of the ceramic bricks. Impact savings due to avoiding the landfilling of the Waelz slag were also considered. A series of scenarios have been defined describing the transport of raw materials and residues, processing and manufacturing of fired clay bricks, and the end-of-life of the construction products. The analysis also covers the effect of alternative waste management scenarios regarding the landfilling and recycling of Construction and Demolition Waste (CDW).

2. Methodology

2.1. Life cycle assessment of fired clay bricks containing Waelz slag

2.1.1. Goal and scope definition

The main goal of this investigation is to quantify the environmental benefits associated with the incorporation of Waelz slag into fired clay bricks, as an alternative to the final disposal of this residue by landfilling. In addition, a secondary goal has also been set involving the analysis of environmental benefits resulting from meeting the recycling objectives for Construction and Demolition Waste (CDW) set under the EU Waste Framework Directive for 2020. This investigation has been carried out using Life Cycle Assessment (LCA) methodology according to standard procedures described under ISO 14040 and ISO 14044 [20,21].

This LCA has been based on an earlier experimental work carried out by authors of the same research group describing the characteristics of ceramic bricks incorporating different proportions of this non-hazardous residue. This investigation proved that fired clay bricks containing up to 20 wt% Waelz slag complied with all the technological specifications and also with the environmental requirements regarding the leaching of potentially hazardous components when disposed of by landfilling [8]. Inventory data for air emissions during the firing process and the leaching of toxic compounds during landfilling derive from this preceding investigation [8,22]. Since both products, the conventional bricks and the waste incorporating bricks, are capable of accomplishing the same functional requirements, the functional unit for this investigation was selected on a product mass basis as "*1 tonne of bricks*".

The LCA has been performed following a cradle-to-grave approach and considering the following four life cycle phases:

- RAW MATERIALS: including extraction of raw materials (natural clay and/or Waelz slag) and transportation to the brick manufacturing plant,
- MANUFACTURING: including the fabrication of the standard or Waelz slag containing ceramic bricks,
- RECYCLING: transport of bricks to the recycling facility at the end of their useful lives, shorting of raw materials and processing for aggregate production.
- LANDFILLING: transport of used bricks from construction site to disposal facility, construction and operation of landfill site, and leaching of toxic inorganics.

Owing to their limited contribution, and also due to the fact that they have a similar contribution in all the scenarios considered, the following processes were left out of the boundaries of the analysis: machinery and equipment at brick manufacturing plant, landfill site and CDW recycling plant; and brick utilization phase (including transport to the construction site, construction activities and demolition of building at the end of its useful life).

2.1.2. System boundaries and scenarios

Fig. 1 shows the life cycle diagram and system boundaries of the three analysis scenarios considered in this investigation:

i) **Standard brick (B-S1) scenario** describes conventional bricks produced from 100 wt% clay. The system boundaries cover the extraction from the quarry of 1.25 tonnes of natural clay, its transportation to the brick factory, the

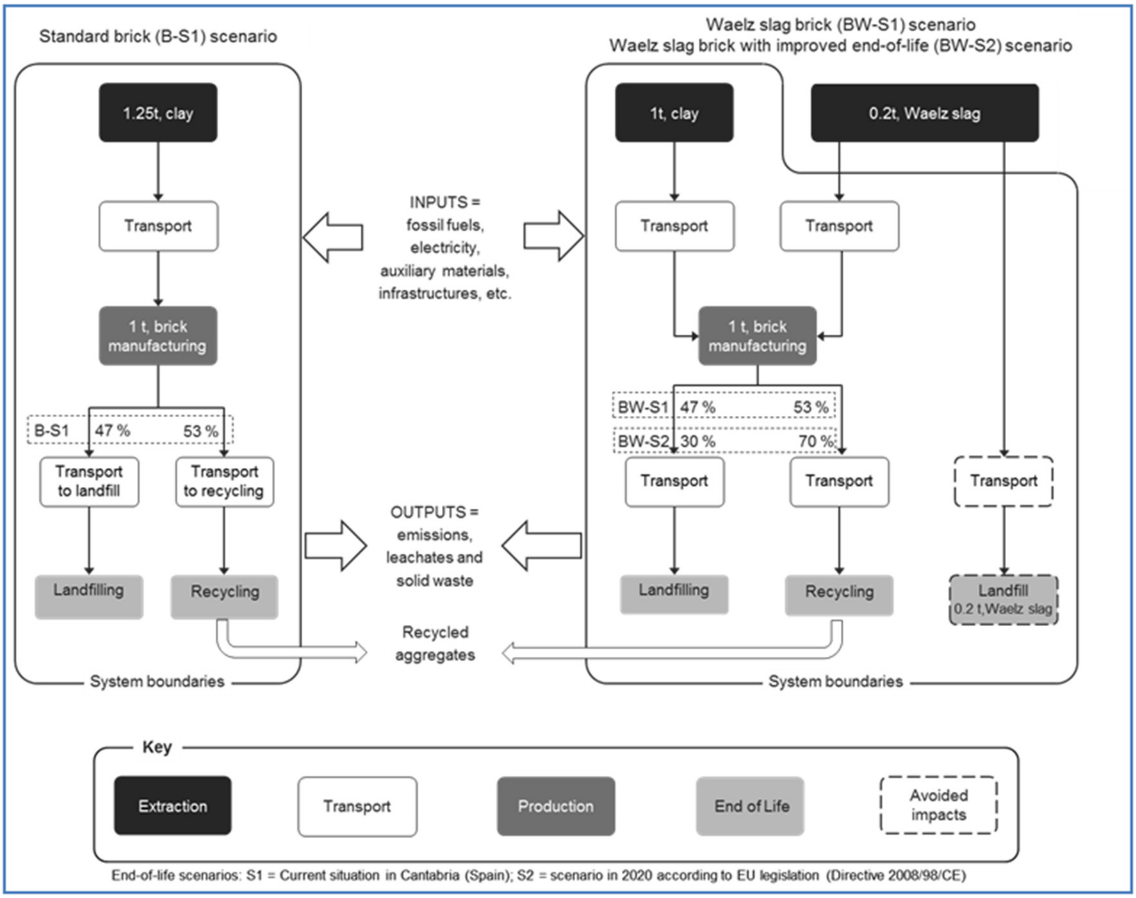


Fig. 1. Life cycle flow chart of standard brick (B-S1), Waelz slag brick (BW-S1) and Waelz slag bricks with improved end-of-life (BW-S2) scenarios.

manufacturing of 1 tonne of standard bricks (including fuel and electricity consumption). Codename S1 represents that the end-of-life of the bricks has been modelled considering the current situation in Cantabria (Spain), as reported by the local Ministry for the Environment (i.e. 53 wt% recycling to construction aggregates and 47 wt% disposal by landfilling) [23].

ii) **Waelz slag brick (BW-S1) scenario** describes alternative bricks where 20 wt% of the natural clay has been replaced by Waelz slag. The system boundaries for this scenario cover the extraction and transportation of 1.00 t of clay from the quarry to the brick factory, the transportation of 0.2 t of slag from the Waelz plant to the brick factory, the manufacturing of 1 tonne of alternative bricks and the management of the bricks at the end of their useful lives as in S1. This scenario considers emission savings (represented as negative impact values) due to avoiding the disposal of Waelz slag (200 kg per tonne of bricks), including transport of the slag to the landfill site and leaching of toxic inorganic species.

iii) **Waelz slag brick with improved end-of-life (BW-S2)** scenario is similar to **BW-S1** but with a higher recycling rate (70 wt%) for CDW, as projected in the EU Waste Framework Directive (2008/98/EC) [24] for 2020.

2.1.3. Life cycle inventory analysis

This section provides the life cycle inventory data employed in the LCA of the brick scenarios. Table 1 illustrates the inventory data for the RAW MATERIALS phase. Impacts associated with the extraction of natural clay are those associated with pit operation while impacts attributable to the extraction of the slag are allocated to the main product of Waelz process (Waelz oxide) and are not considered due to the residual nature of this material. The clay pit has been assumed adjacent to the brick manufacturing plant, thus requiring no transportation. Inventory data for the MANUFACTURING phase takes into consideration two emission sources: first, the consumption of energy in the form of electricity, diesel and natural gas at the brick manufacturing plant; and second, direct emissions in the form of CO_2, SO_2, NOx, HCl and HF generated by the thermal transformation of the raw materials (natural clay and Waelz slag) during the firing process. The negligible SO_2 and HCl emissions observed in the firing of standard bricks has been associated to the low S and Cl concentrations in the natural clay and also the retention of these gas emissions by alkaline and earth-alkaline oxides present in the clay [22]. The higher gas emissions generated by the alternative bricks is due to the significantly higher concentration of these elements (F, Cl, S) in the slag. In contrast, NOx emissions are lower in Waelz slag bricks due to the lower firing temperatures achieved. Table 2 illustrates the background inventory data for the RECYCLING and LANDFILLING phases, and foreground data regarding the leaching of inorganics at the end of the useful lives of the bricks. Table 3 describes the inventory data employed to model the landfilling of Waelz slag, including construction and operation of the landfill site, and the leaching of toxic inorganic species.

Foreground inventory data was obtained from the following sources: i) gas emissions due to the thermal transformation of natural clay and Waelz slag from experimental investigations described in [25]; ii) leaching of toxic inorganics from standard bricks (B-S1), Waelz slag bricks (BW) and Waelz slag from experimental investigations described in [8]; iii) energy and material inputs in the brick plant, and transport distances and conditions

Table 1
Inventory data for RAW MATERIALS and MANUFACTURING adjusted to 1 tonne of bricks including: extraction and transport of raw materials (top), energy inputs at the brick manufacturing plant (middle) and direct emissions from thermal processing of raw materials (natural clay and Waelz slag) during firing.

Elementary flow	Unit	Standard brick (B-S1)	Waelz slag brick (BW-S1)	LCIA dataset
Extraction and transport of raw materials				
Clay	tonne	1.25	1	Clay/CH/pit operation/Conseq, U
Waelz slag	tonne	0	0.2	–
Transport clay	tkm	0	0	–
Transport Waelz to manufacturing plant	tkm	0	27.6	Transport, freight, lorry 16–32 metric tonne, EURO5 {GLO}| market for | Alloc Def, U
Energy and material inputs at brick manufacturing plant				
Electricity	MWh	50	42.5	Electricity, medium voltage/ES/market for/Conseq, U
Natural Gas	MJ	1664	1433	Electricity, high voltage/ES/ Electricity production, natural gas, at conventional power plant /Conseq, U
Diesel	MJ	405	347	Diesel, burned in building machine/GLO/market for / Conseq, U
Brick production facility	p(*)	$3.3^{*}10^{-6}$	$3.3^{*}10^{-6}$	Brick production facility {RoW}| brick production facility construction | Alloc Def, U
Direct emissions due to thermal transformation of raw materials (natural clay and Waelz slag) [22]				
CO_2	g	6487	5030	Emissions to air – CO_2
SO_2	g	0	1763	Emissions to air – SO_2
NO_X	g	1177	922	Emissions to air – NO_X
HCl	g	0	597	Emissions to air – HCl
HF	g	116	772	Emissions to air – HF

(*) "p" is used as a convention in ecoinvent datasets to designate the number of "Construction of landfill site" units associated with a functional unit of the system (1 tonne of bricks).

Table 2
Inventory data for the RECYCLING and LANDFILLING of 1 tonne of bricks including: energy, material and transport inputs derived from disposal activities (top), leaching of toxic species at landfill site (middle), and energy and transport inputs of recycling under waste management scenarios S1 and S2.

Elementary flow	Unit	Standard brick	Waelz slag brick		LCIA dataset
		B-S1	BW-S1	BW-S2	
Energy and material inputs at landfill site – landfilling of CDW					
Landfilling CDW	%	47	47	30	
Construction of landfill site	p	$0.31^{*}10^{-6}$	$0.31^{*}10^{-6}$	$0.20^{*}10^{-6}$	Inert material landfill {RoW}| construction | Alloc Def, U
Transport CDW to landfill	tkm	103	103	66.0	Transport, freight, lorry 16–32 metric tonne, EURO5 {GLO}| market for | Alloc Def, U
Clay for daily cover in landfill	kg	16.2	15.3	9.78	Clay {RoW}| clay pit operation | Alloc Def, U
Sand for intermediate cover in landfill	kg	3.44	3.25	2.07	Gravel, round {RoW}| gravel and sand quarry operation | Alloc Def, U
Electricity for landfill operation	kWh	0.081	0.081	0.052	Electricity, medium voltage {ES}| market for | Alloc Def, U
Diesel for landfill operation	MJ	10.8	10.2	6.51	Diesel, burned in building machine {GLO}| market for | Alloc Def, U
Water for landfill operation	kg	22.1	22.1	14.1	Water, fresh
Leaching of toxic species at landfill site – landfilling of CDW					
Zn	mg	282	329	210	Emissions to soil – Zn
Ba	mg	<d.l.	517	330	Emissions to soil – Ba
Mo	mg	<d.l.	1410	900	Emissions to soil – Mo
Recycling of CDW					
Recycling CDW	%	53	53	70	
Transport CDW to CDW plant	tkm	122	122	162	Transport, freight, lorry 16–32 metric tonne, EURO5 {GLO}| market for | Alloc Def, U
Electricity for shorting (before plant)	kWh	1.96	1.96	2.59	Electricity, medium voltage {ES}| market for | Alloc Def, U
Diesel for shorting (before plant)	MJ	2.17	2.17	2.86	Diesel, burned in building machine {GLO}| market for | Alloc Def, U
Electricity for CDW treatment plant	kWh	0.44	0.44	0.58	Electricity, medium voltage {ES}| market for | Alloc Def, U
Diesel for CDW treatment in plant	MJ	7.09	7.09	9.4	Diesel, burned in building machine {GLO}| market for | Alloc Def, U
Recycled products (as avoided impacts)	t	0.53	0.53	0.70	Gravel, crushed {CH}| production | Alloc Def, U

d.l.: detection limit in leachates, Ba < 0.02 mg/l and Mo < 0.122 mg/l [22].

for raw materials (clay and Waelz slag) and CDW in the recycling phase were provided by local brick manufacturers and CDW recycling plants in Cantabria (Spain); iv) materials and energy inputs at the landfill site were adapted from data reported in national regulations [26] using the methodology proposed at [27]. Ecoinvent v.3 was used for background inventory data [28] and specific datasets used in the modelling of the systems are included in Tables 1–3.

2.1.4. Life cycle impact assessment methodology

Life Cycle Impact Assessment (LCIA) methods ReCiPe Midpoint (Europe H) v. 1.13 and ReCiPe Endpoint (Europe H/H) were used to transform emission values into impact category indicators and damage indicators, respectively. ReCiPe Midpoint (Europe H) v.1.13 is also used to normalize emission values. This selection is based on the recommendations proposed in the product category rules established for construction materials ISO 15804:2012 [6] and the need for consistency in the application of midpoint and endpoint methods (ReCiPe created by the same developers as an updated version of CML 2001 and Ecoindicator 99). Ten impact categories were considered for midpoint analysis including: Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Human toxicity, Photochemical oxidant formation,

Table 3
Inventory data for the disposal of 1 tonne of Waelz slag by landfilling including: landfill operation (top) and leaching of toxic species.

Elementary flow	Unit	Waelz slag	LCIA dataset
		Landfilling operation for disposal of Waelz slag	
Landfilling Waelz slag	tonne	1.0	
Construction of landfill site	p	$0.66*10^{-6}$	Inert material landfill {RoW}| construction | Alloc Def, U
Transport Waelz slag to landfill	tkm	104	Transport, freight, lorry 16–32 metric tonne, EURO5 {GLO}| market for | Alloc Def, U
Clay for daily cover in landfill	kg	16.8	Clay {RoW}| clay pit operation | Alloc Def, U
Sand for intermediate cover in landfill	kg	3.57	Gravel, round {RoW}| market for gravel, round | Alloc Def, U
Electricity for landfill operation	kWh	0.175	Electricity, medium voltage {ES}| market for | Alloc Def, U
Diesel for landfill operation	MJ	11.1	Diesel, burned in building machine {GLO}| market for | Alloc Def, U
Water for landfill operation	kg	47.0	Water, fresh
		Leaching of toxic species due to landfilling of Waelz Slag	
As	mg	60	Emission to soil – As
Ba	mg	113,000	Emission to soil – Ba
Cr	mg	7670	Emission to soil – Cr
Cu	mg	430	Emission to soil – Cu
Mo	mg	4610	Emission to soil – Mo
Pb	mg	608,700	Emission to soil – Pb
Zn	mg	4270	Emission to soil – Zn
Cl^-	mg	9,932,000	Emission to soil – Cl^-
F^-	mg	132,500	Emission to soil – F^-

Particulate matter formation, Terrestrial and Freshwater ecotoxicity and Fossil depletion. The endpoint methodology considered three categories: Depletion of resources, Damage to human health and Damage to ecosystem quality. Endpoint indicators were aggregated using the weighing factors proposed by the ReCiPe authors. SimaPro v8.3 software was used to build the models and perform calculations.

Regarding air emissions, it is noteworthy considering in the discussion that ReCiPe Midpoint (Europe H) v. 1.13 stipulates that HF emissions have an effect only on the Human toxicity category while HCl emissions are not considered in any of the impact categories evaluated. Soil emissions resulting from leaching of inorganics (As, Ba, Cr, Cu, Mo, Pb, Zn) from bricks and Waelz slag have effects on the Human toxicity, Terrestrial ecotoxicity and Freshwater ecotoxicity categories. In contrast, chloride (Cl^-) and fluoride (F^-) emissions in the leachates are not considered in any of the categories of this LCIA methodology.

3. Results and discussion

3.1. Impact oriented analysis of standard and Waelz slag bricks

Fig. 2 illustrates the impacts associated with the life cycle of 1 tonne of standard bricks produced from 100 wt% natural clay. The impact on climate change of the system represents 238 kg of CO_2 eq./tonne of bricks, a value that is comparable to those reported by other authors for the fabrication of fired clay bricks as [13,14,17] showing values of 221, 271 and 195 kg of CO_2 eq./tonne of bricks respectively. Most of this impact (80%) is attributable to the manufacturing phase, in particular the combustion of fossil fuels (49.9% to natural gas and 15.9% to diesel) and the use of electricity (10.1%) during the firing process. Only 2.7% of the impact on this category correspond to direct emissions derived from the thermal transformation of the natural clay (6.49 kg of CO_2 eq./tonne of bricks, as shown in the inventory data of Table 1). The landfilling and recycling phases each one account for 8% of this impact category, while the extraction of the raw materials (natural clay) and its transport from the quarry to the brick factory contribute to only 4% of the total.

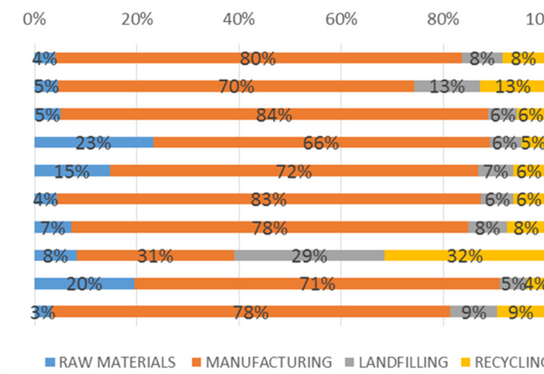
The manufacturing stage is also the main contributor to impact generation on all other categories (between 66% and 86%). This is due, in most cases, primarily to the consumption of natural gas and other energy requirements. However, in the case of the terrestrial acidification category, most of the impact (47% of the total, equivalent to 1.42 kg SO_2 eq./tonne of brick) is attributable to NOx emitted directly by the clay during the calcination process. In the case of the human toxicity category, not only the NOx emissions, but also direct emissions of HF due to calcination of the clay are the main contributors (30.9 kg of 1,4-DB eq./tonne of bricks, representing 42% of the total).

On the contrary, for the terrestrial ecotoxicity category, the environmental deterioration is mainly attributable to the end of life phase. In particular, brake wear emissions associated with transport activities is the most damaging action, contributing to 57% and 62% of the impact on this category in the landfilling and recycling phases, respectively.

Fig. 3 shows the environmental performance of 1 tonne of bricks manufactured with 20 wt% Waelz slag with information about the contribution of different life cycle phases. As explained in the methodology section, this system scenario takes into consideration emission saving caused by avoiding the disposal of 200 kg of Waelz slag. Savings calculated for the Waelz slag landfilling system are represented as negative impact values and deduced from the ones calculated for the Waelz slag bricks.

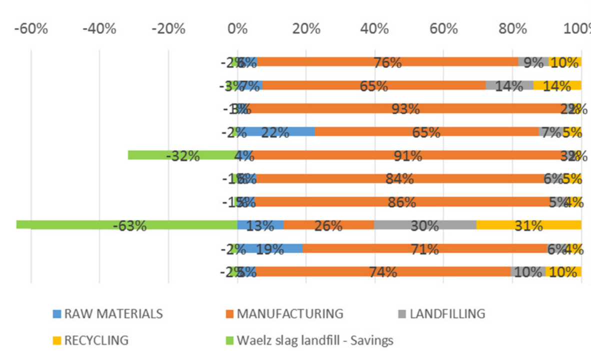
The environmental profile of Waelz slag bricks is very similar to that observed in standard bricks where most impact categories are dominated by the manufacturing phase (between 65% and 93%). Regarding the climate change category, the results show that impact generated by Waelz slag bricks (210 kg of CO_2 eq./tonne of bricks) is 11.8% lower than that of conventional bricks. Impact savings from avoiding the landfilling of the slag only contributes to reducing 4 kg of CO_2 eq./tonne of bricks. The rest (24 kg of CO_2 eq./tonne of bricks) is due primarily to the inferior energy requirements (natural gas, diesel and electricity) during the manufacturing stage. Being Waelz slag a metallurgical waste generated at very high temperatures, it does not undergo the endothermic transformations (mainly dehydration and decarbonation reactions) which occur in the conversion of natural clay when fired. The lower fuel requirements and temperatures achieved result in reduced NOx and CO_2 emissions, as shown in the inventory data of Table 1. However, the presence of sulphur, fluorine and chlorine in the slag favours the air emission of SO_2, HCl and HF into the air during firing.

This prevalence of the manufacturing phase does not occur in the terrestrial ecotoxicty category. As discussed in the analysis of standard bricks, this observation is attributable primarily to the high impact generated by transport activities in the recycling and landfilling stages of the system.



Impact category	Units	Total
Climate change	kg CO2 eq	238
Ozone depletion	kg CFC-11 eq	0.000029
Terrestrial acidification	kg SO2 eq	1.42
Freshwater eutrophication	kg P eq	0.0255
Human toxicity	kg 1,4-DB eq	73.9
Photochem. oxidant formation	kg NMVOC	1.70
Particulate matter formation	kg PM10 eq	0.5344
Terrestrial ecotoxicity	kg 1,4-DB eq	0.0278
Freshwater ecotoxicity	kg 1,4-DB eq	1.267
Fossil depletion	kg oil eq	78.2

Fig. 2. Characterized impacts associated with 1 tonne of standard fired clay bricks (B-S1) and contribution from different life cycle stages.



Impact category	Units	Sub-total	Waelz slag landfilling	TOTAL
Climate change	kg CO2 eq	214	-4.0	210
Ozone depletion	kg CFC-11 eq	0.000027	-0.000001	0.000026
Terrestrial acidification	kg SO2 eq	2.97	-0.01	2.95
Freshwater eutrophication	kg P eq	0.0227	-0.0003	0.0223
Human toxicity	kg 1,4-DB eq	246.6	-78.3	168.3
Photochem. oxidant form.	kg NMVOC	1.56	-0.02	1.54
Particulate matter form.	kg PM10 eq	0.8107	-0.0078	0.8028
Terrestrial ecotoxicity	kg 1,4-DB eq	0.029	-0.018	0.011
Freshwater ecotoxicity	kg 1,4-DB eq	1.122	-0.023	1.099
Fossil depletion	kg oil eq	70.8	-1.6	69.2

Fig. 3. Characterized impacts associated with 1 tonne of fired clay bricks incorporating 20 wt% Waelz slag (BW-S1) and contribution from different life cycle stages (including impact savings due to avoiding the landfilling of 200 kg of Waelz slag).

Impact savings derived from avoiding the disposal of Waelz slag are significant only on two categories: human toxicity and terrestrial ecotoxicity categories. This is due to environmental damage caused by the leaching of inorganic species when the Waelz slag is disposed by landfilling (and avoided when the slag is incorporated into the ceramic materials). The impact generated by these soil emissions represent 78.3 kg 1,4-DB eq./tonne of bricks in the human toxicity and 0.018 g 1,4-DB eq./tonne of bricks in the terrestrial ecotoxicity categories. Impact savings on all other categories due to avoiding the landfilling of Waelz slag are limited (<3% of the sub-total determined for the Waelz bricks).

The situation is noteworthy in the human toxicity category, where the impact of Waelz slag bricks (168 kg 1,4-DB eq./tonne of bricks) has been calculated to be 127% higher than that of standard bricks. The incorporation of slag into the bricks results in higher air emissions of HF during the firing process (as shown in inventory data of Table 1). Impact savings in this category due to avoiding soil emissions derived from the landfilling of Waelz slag (−78.3 kg 1,4-DB eq./tonne of bricks) are not sufficient to compensate impact generated from air emission of HF.

Fig. 4 illustrates comparatively the impacts generated by the three system scenarios considered in this investigation (standard bricks B-S1, Waelz bricks BW-S1 and Waelz bricks with improved end of life BW-S2) on each of the ten environmental categories selected. The standard brick scenario is used as a reference receiving a value of 100%. The results evidence that the improved end-of-life scenario (BW-S2) generated lower impact on all categories than the conventional scenario for Waelz slag bricks (BW-S1). However, this improvement is below 1% in all impact categories, except for terrestrial ecotoxicity that was reduced by 2.7%. This effect is due to the fact that impact savings derived from the generation of additional recycled aggregate in a higher recycling rate scenario, are very low and they are offset by the negative impacts associated with the transportation and processing of the CDW itself.

In contrast, notable differences were observed between the standard (B-S1) and Waelz slag (BW-S1) bricks, not always benefiting the alternative materials. As discussed above, impact values on climate change were 11.8% lower in bricks containing Waelz slag, and similar improvements were observed on other impact categories like ozone depletion (10.6%), freshwater eutrophication (12.4%), photochemical oxidant formation (9.4%), freshwater ecotoxicity (13.3%) and fossil depletion (11.5%). Environmental improvements in the terrestrial ecotoxicity category were significantly greater with impact values 63% lower in the Waelz slag bricks than in standard ceramics. As discussed, this improved environmental performance is due primarily to impact savings achieved from avoiding the landfilling of the Waelz slag (avoiding the leaching of potentially toxic inorganic species).

Terrestrial acidification and particulate matter formation impacts are higher mainly to the SO_2 and NOx emissions generated as result of producing the Waelz slag bricks. Human toxicity impact is higher due mainly to the HF emission, with a high characterization factor of 2800, during manufacturing Waelz slag bricks; this increase cannot be compensated from the fluoride (F^-) emissions avoided in the leachates during the landfilling of the Waelz slag, because are not accounted in any of the categories of this LCIA methodology.

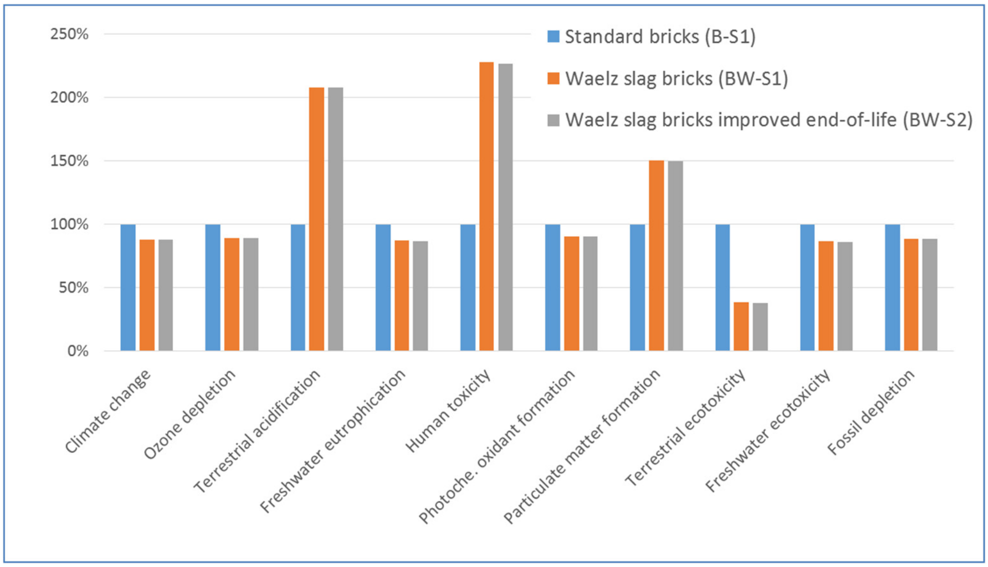


Fig. 4. Comparative impact values of standard (B-S1), Waelz slag bricks (BW-S1) and Waelz slag bricks with improved end-of-life (BW-S2) for different categories.

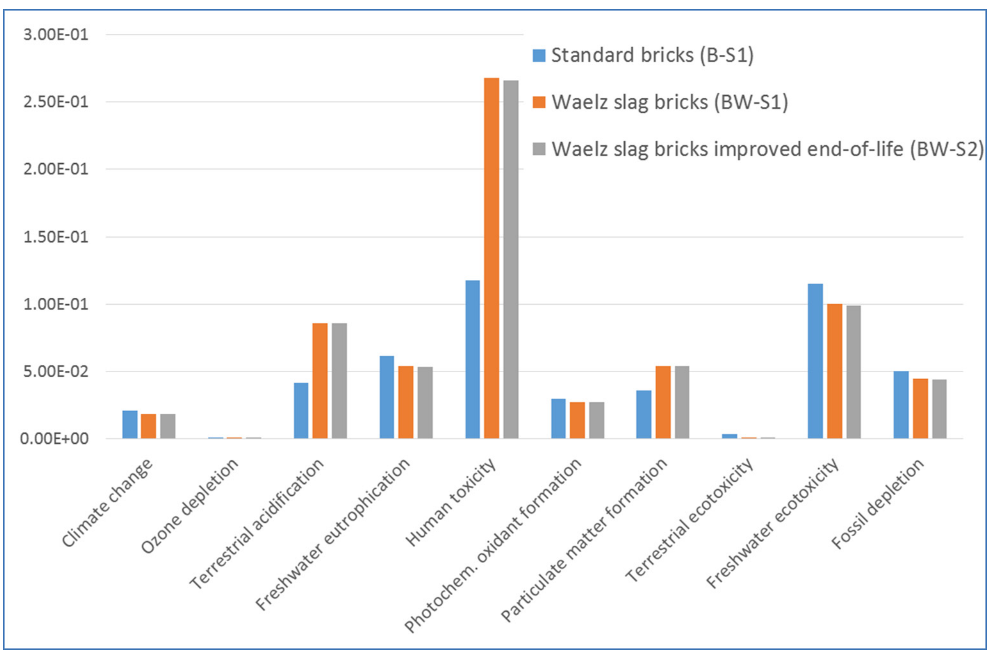


Fig. 5. Normalized impact values determined for standard bricks (B-S1), Waelz slag bricks (BW-S1) and Waelz slag bricks with improved end-of-life (BW-S2).

3.2. Normalized analysis of standard and Waelz slag bricks

Fig. 5 illustrates the normalized results obtained when comparing the three system scenarios investigated in this work. The results evidence that the impact categories most significantly affected by the systems are related to toxicity (Human toxicity and Freshwater ecotoxicity). This is followed at a distance by terrestrial acidification, freshwater eutrophication and other categories like fossil depletion and photochemical oxidant formation. The significance of impact on the climate change was less significant, according to this methodology.

3.3. Damage oriented analysis of standard and Waelz slag bricks

Fig. 6 illustrates the damage oriented analysis of the three scenarios considered in this investigation. The aggregated results suggest that the differences in environmental performance of the three scenarios are not very significant, with single point indicators ranging between 26.2pt. in standard bricks (B-S1) and 24.9pt. in Waelz slag bricks with improved end-of-life (BW-S2).

The results suggest that standard bricks perform comparatively better (smaller damage) than Waelz slag bricks in the human health category. However, this benefit is compensated by the reduced impact of the slag bricks in terms of resources depletion and ecosystems quality. As described using the midpoint approach, the application of the improved end-of-life scenario only has a very marginal effect on environmental performance of the brick system, because greater recycling leads to less landfilling impact but greater impacts of the recycling plant mainly due to the material transport and electricity consumption. The extension of the LCA study boundaries to the application of the aggregates could reflect the potential benefits of greater recycling.

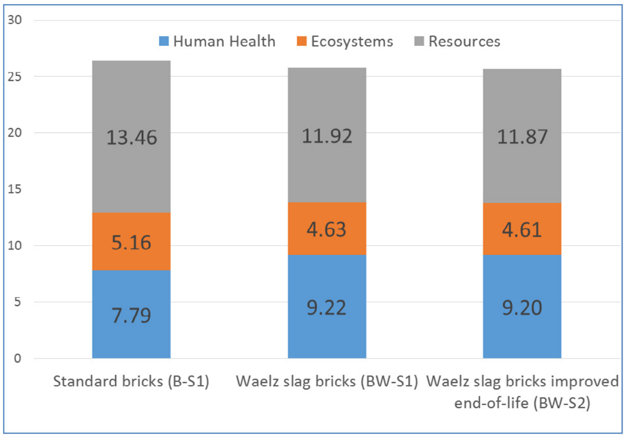


Fig. 6. Single point damage oriented results describing the life cycle analysis of standard bricks (B-S1), Waelz slag bricks (BW-S1) and Waelz slag bricks with improved end-of-life scenario (BW- S2).

4. Conclusions

This paper describes an investigation aimed at quantifying the potential environmental benefits of the Waelz slag incorporation to fired bricks as practical example of industrial ecology. The life cycle phase most significantly affecting the environmental performance of the fired conventional bricks and Waelz slag bricks is manufacturing, due primarily to the energy intensiveness of the process (natural gas, diesel and electricity), and also due to direct air emissions produced by the thermal decomposition of the raw materials (both natural clay and Waelz slag). Impact savings due to avoiding the landfilling of Waelz slag are related to leaching of inorganic species during landfilling.

The incorporation of Waelz slag waste reduces the extent of endothermic reactions that take place during the manufacturing of the ceramic product, thus reducing fuel consumption. As a result, the impact on climate change of Waelz slag bricks was 11.8% lower than that of standard bricks. Similar impact reductions were observed on other impact categories like ozone depletion (10.6%), freshwater eutrophication (12.4% lower impact), photochemical oxidant formation (9.4%) and fossil depletion (11.5%). However, the presence of sulphur and fluorine in the Waelz slag favours the emission of toxic and acidifying species like SO_2 and HF during firing, thus promoting environmental impacts on other categories like terrestrial acidification (108% higher impact), particulate matter formation (50.2%) and human toxicity (128%).

The aggregated analysis conducted using a damage oriented approach shows that the benefits of incorporating Waelz slag into fired bricks is very limited. Although Waelz slag bricks performed comparatively better (smaller damage) than standard bricks in the resources depletion and ecosystems quality categories, this was compensated by a worse performance (higher damage) in the human health category.

Some of the emissions associated with the life cycle of standard and alternative bricks (i.e. soil emission of chlorides, fluorides and air emissions of HCl) are not included in the ReCiPe LCIA methodology employed in this investigation. These species are not included in other widely used LCIA methods like CML, ILCD, IMPACT2000 or other more specialized on toxicity analysis like USEtox. Incorporation of these emissions into the LCIA may affect the final results.

The comparative cradle to gate LCA analysis provide environmental criteria for decision making in the incorporation of Waelz slag in fired clay brick, being extensible to other products in the construction / building material sector. A deep analysis of the process gas emissions and the inclusion in the LCA of the toxicity related impact categories of the chemicals with proven toxicity and adverse effects on human health and aquatic ecosystem as F^-, Cl^- and HCl (g) it is highlighted in the context of the Construction Product Declaration of materials incorporating wastes.

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